Indian J. Phys. 75A (3), 215-217 (2001)

Rapid Communication

IJP A
– an international journal

Existence of stop-bands for ultrasonic longitudinal waves propagating in wood

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Received 27 April 2001, accepted 3 May 2001

Abstract The annular ring structure of wood represents a quasi-periodic elastic structure Ultrasonic waves propagating normal to the rings (in the radial direction) have been shown to exhibit stop-bands consistent with the classical theory for such structures

Keywords Ultrasonic, attenuation, wood, stop-bands

PACS Nos. 43.35 Cg

1. Introduction

There has been considerable interest in the propagation of ultrasonic waves in wood [1] both as a means of investigating the strength of the wood and as a potential method of assessing the wood quality of trees *in situ*. The anisotropy of wood is evident and the most common theoretical model used for ultrasonic propagation is that of a lossless (homogeneous) orthotropic solid [2]. Such materials require only 9 elastic constants fully to determine the stiffness matrix. In general, three waves can be generated in a given direction of propagation. Along the principal axes in orthrotropic solids, these are pure modes – one longitudinal and two transverse (with mutually perpendicular polarizations). In directions other than along the principal axes the modes are in general not pure – the polarization is not exactly aligned with or perpendicular to the direction of propagation – and are called quasi-longitudinal or quasi-transverse waves. It appears that conversion of waves between modes can occur as they propagate off axis [3].

A recent extended set of measurements of ultrasonic velocity and attenuation in the frequency range 100 kHz to 1.5 MHz [4–6] revealed that even such bulk wave measurements are affected by the different levels of inhomogeneity in the wood. While these occur with dimensional scales ranging from microns to cm [7], the most obvious is that of the annular growth ring structure. Considering this as a structure whose elastic properties vary periodically, it might be expected that it would exhibit pass bands and stop-bands in the dispersion curves. The present communication presents a brief numerical discussion of the possibility of the existence of such bands in practice, together with preliminary evidence of the existence of a stop band.

2. Theoretical considerations

The basic analysis of elastic wave propagation in periodic structures is well known if not elementary [8]. The application of this theory to wood is complicated by several factors. Firstly, wood is an immensely variable material [4] : two specimens from the same tree may have differing properties. Secondly, the environmental history of the tree is the primary factor determining the properties and (especially) the geometry and regularity of the annular ring structure : it may vary even from one side of a tree to the other if "reaction" wood is present [9]. Thirdly, rather than exhibiting discrete bands of differing elastic properties, the properties tend to vary in a continuous fashion. Fourthly, the determination of the relevant elastic properties (density and elastic modulus) of the rings actually comprising a particular specimen is presently impractical. While the density distribution may be obtained by X-ray densitometry, no satisfactory

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technique currently exists for measuring the variation of the longitudinal wave velocity along the radial axis of the wood

Two further factors may confound an experimental search for the existence of ultrasonic stop-bands and pass-bands. Firstly the ring structure is, at best, only quasi-periodic, and secondly experiments can only be made on specimens with a finite number of periods of variation rather than the infinite array assumed by the theory. Previous studies have shown that the attenuation of longitudinal waves along the radial axis is considerably higher than along the longitudinal and tangential axes of the timber [5, 6]. While this itself is strong evidence for the influence of the annular ring structure on ultrasonic propagation, it means that the finite number of periods that can be used in an experimental specimen is limited to a maximum of the order of 10. If the rings were exactly periodic, even this could be enough for stop-bands to be observed [10]. It is possible in principle, to use lower frequencies (where the attenuation is lower) to be able to traverse a larger number of rings, but at such frequencies, the width of the rings becomes very much less than the wavelength of the ultrasound being used.

In order to gain some numerical insight into the potential existence of stop-bands and pass-bands in wood, it was assumed that each annual ring was identified and consisted of a layer of early wood and a thinner layer of (denser) latewood. A set of typical values for the dimensions and elastic parameters for hardwood and for softwood is given in Table 1. The layer thicknesses and typical density variations were taken from X-ray densitometry scans and from the literature. The values for the velocity variations were harder to estimate. There appears to be no directly relevant data available, due to the difficulty of measuring it. Data is available on the velocity variation in the early wood and late wood for longitudinal waves propagating in the tangential direction [6]. The stiffness of wood in the tangential direction is comparable to that in the radial direction [11], so that as a first approximation, it is reasonable to assume that the velocity variation between the early wood and late wood in the radial direction is the same in ratio terms as that in the tangential direction.

Table 1. Typical values of the dimensions and mechanical parameters of early wood and late wood rings in softwood and hardwood.

Parameter	Hardwood (Ring Porous)	Softwood
Early wood thickness	0.5 mm	4.5 mm
Early wood velocity	2000 m/s	1800 m/s
Early wood density	400 kg/m^3	300 kg/m^3
Late wood thickness	0.5 mm	0.8 mm
Late wood velocity	2200 m/s	2400 m/s
Late wood density	700 kg/m^3	700 kg/m^3

From the data in Table 1, it is possible to predict the pass-bands and stop-bands that could be observed. Figure 1 shows partial results of the calculations, while Table 2 lists the stop-bands calculated. It is clear that the wider spacing of the softwood rings and the greater differences in the elasti

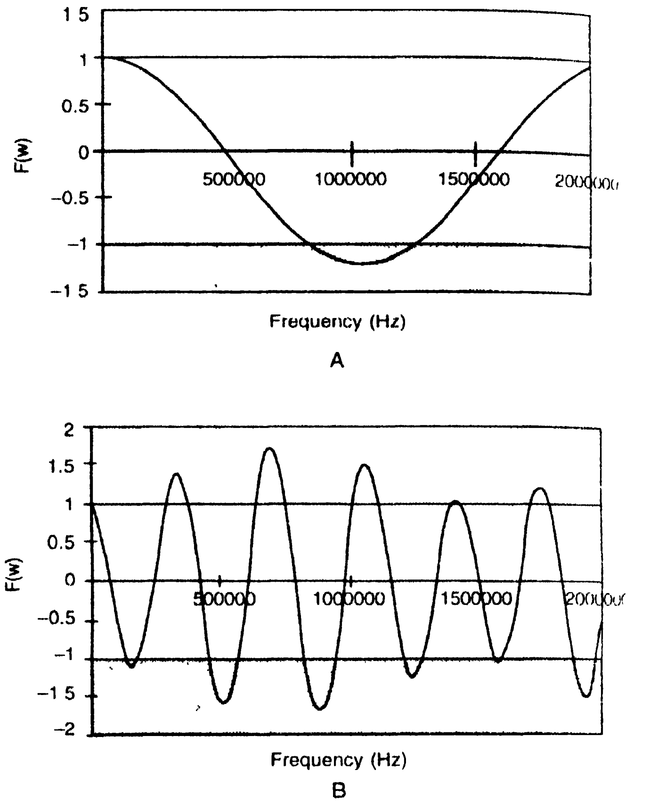

Figure 1. Calculations of the stop-bands for ultrasonic waves using data of Table 1 for A) hardwood and B) softwood

Table 2. Stop-bands calculated for A) softwood, and B) hardwood

Stop-band Number	Lower Limit of Stop-band (kHz)	Upper Limit of Stop-band (kHz)
1	144	190
2	300	382
3	470	572
4	650	758
5	834	942
6	1,024	1,116
7	1,214	1,280
8	1,406	1,428
9	1,572	1,594
10	1,720	1,786
11	1,884	1,976

(A)

Stop-band Number	Lower Limit of Stop-band (kHz)	Upper Limit of Stop-band (kHz)
1	834	1,260

(B)

parameters between early wood and late wood give rise to a much greater range of stop-bands in softwood than in hardwood. The softwood and hardwood are both predicted to have stop-bands at frequencies in the region of 1 MHz.

3. Results

Experimental investigation of the possible presence of stop-bands was attempted on specimens of two European softwoods Scots Pine and Norway Spruce. A nominal 2MHz ultrasonic transducer (20 mm element diameter) was shock-excited to produce a short (broad band) ultrasonic pulse in the specimens. The signals transmitted through the wood were detected with a transducer identical to the transmitter. Coupling of the ultrasonic transducers to the specimens was achieved by dry coupling, with the assistance of a torque wrench to ensure consistent coupling pressure. The recorded signals were digitised and Fourier transformed to provide the equivalent frequency spectra. A stop-band is identified as a sharp trough in the spectrum of the recorded signal.

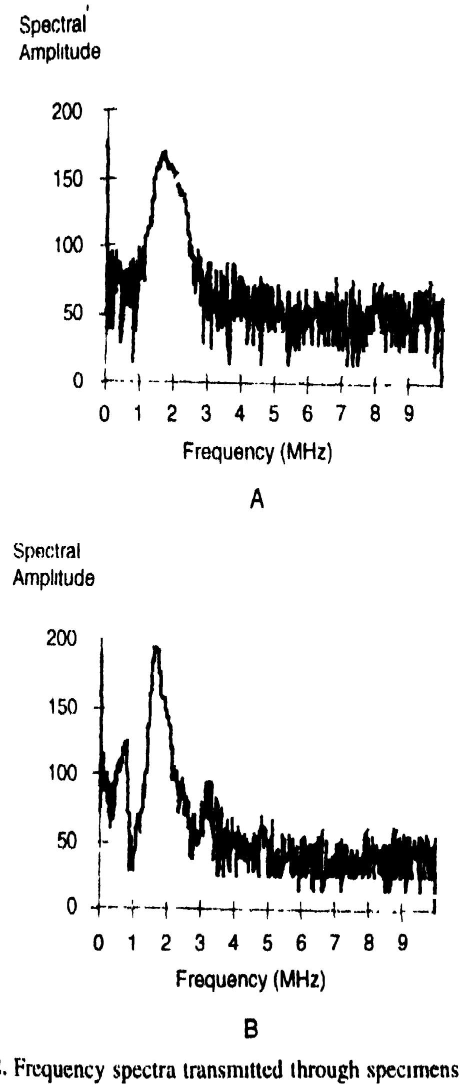

Figure 2. Frequency spectra transmitted through specimens of : A) Norway Spruce and B) Scots Pine.

The results are shown in Figure 2. It can be seen that the Spruce sample (Figure 2A) has a smooth transmission spectrum which does not exhibit clear stop-bands. This may be due to the fact that the specimen used had wide, irregularly spaced annular rings. In contrast the Scots Pine sample (Figure 2b) had quite regular narrow rings (~ 1 mm in width). The narrower rings would tend to increase the width of any stop-bands. It can be seen that there is clear evidence of a stop-band at frequencies just above 1MHz.

4. Conclusion

As was indicated above, the presence of stop-bands in ultrasonic propagation in the radial direction of wood specimens will depend essentially on the highly variable parameters of the individual specimens investigated. Thus there are many factors that can militate against the observation of stop-bands. However a regular ring structure can produce stop-bands and the authors believe that this report is the first to provide experimental evidence of the potential presence of such stop-bands.

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